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Quantitative Estimation of Variability in the Underwater Radiance Distribution (RADCAM)

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LONG-TERM GOALS

A significant source of uncertainty in the prediction of the apparent optical properties of the ocean is the geometrical distribution of the radiance field and its variation with respect to time and space; this uncertainty directly affects attempts to use measurements of reflectance and attenuation for the diagnosis of ocean constituents. Uncertainties in the time and depth dependent variations in the radiance distribution, and their sources of variation, propagate as well to the prediction of the performance of new imaging systems such as the "virtual periscope". The problem starts at the sea surface, where the generally unknown sky radiance distribution, coupled with a roughened air-sea interface, plays a major role in the transmission of sun and sky radiance to below the surface. In the ocean interior, the volume scattering function, and the absorption coefficient alter the radiance distribution in both the forward and backward direction; in the perhaps usual situation of multiple scattering, the uncertainty in the radiance distribution becomes large. In optically shallow areas, non-Lambertian bottom reflectances add to the uncertainty.

Our long-term goal is to develop and deploy a relatively simple means for the measurement of the full radiance distribution, which could be routinely deployed by the optical oceanographic community. A further side benefit would be that many of the measurements currently made, such as planar and scalar irradiance, angle-dependent Q factor etc., could be made by various integration operations on the measured radiance field rather than with mechanical diffusers. The potential interferences of various deployment platforms (e.g. shading, reflectances by ships, buoys and towers) could be measured directly rather than inferred based on inaccurate assumptions about the underwater radiance distribution. A direct confirmation of the asymptotic radiance distribution can be made. Finally, high quality quantitative (and radiometrically calibrated) measurements of the radiance distribution, and their time and depth derivatives, can in principle (but not yet in practice) be used to estimate all the inherent optical properties (both absorption and volume scattering coefficient) and as well the nature of the air-sea interface.

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OBJECTIVES

The Radiance Camera or RadCam project is part of the Radiance in a Dynamic Ocean (RaDyO) program. The primary objective is to create a camera that can record the spatial radiance distribution at the ocean surface and at depth. The proposed instrument will be uniquely capable of resolving both the downwelling and upwelling radiance distribution and its variation with depth, time and wavelength ($L(z,t,\theta,\phi,\lambda)$); from these measurements, the apparent optical properties E_D, E_U, E_o, E_{ou} and E_{od} are computed by integration. The distribution functions (e.g. the average cosines) are computed directly, as are the various diffuse attenuation coefficients and reflectances. The fully-specified radiance field therefore provides all the pertinent information to derive not only the apparent optical properties, but the inherent optical properties: the absorption coefficient and, in principle by inversion, the volume scattering function. An instrument capable of this measurement to the necessary accuracy, resolution, and noise characteristics could, again in principle, replace all or most of the optical instruments currently deployed today.

APPROACH

While radiance cameras have been built before, they have not been able to image the sun at the surface due to the very high scene dynamic range. RadCam takes advantage of recent developments in high-dynamic range (HDR) CMOS imaging arrays. These arrays were developed for science, surveillance, and automotive applications. Traditional CCD arrays are linear, limiting the dynamic range that can be achieved. These HDR CMOS arrays use a number of different methods to produce a nonlinear response function, giving scene dynamic ranges of up to 120 dB or 6 decades.

WORK COMPLETED

In the first year of this project we considered several possible cameras and imaging arrays. We tested two candidate cameras/arrays and selected one for RadCam. Measurements showed operate with a scene dynamic range of 6 decades and an impressive system dynamic range of nearly 10 decades.

Three instruments have now been designed and successfully deployed as part of this project. The first is a reference camera mounted on deck. The second is a logging-type instrument that has been mounted on a Bluefin AUV, on an ROV or as an independent tethered underwater unit. The third is a profiler that sends data to the surface for real-time processing. The first two cameras are upward looking only (i.e. they record downwelling radiance) while the profiler has both an upwelling and downwelling camera. This allows it to measure radiance over the entire sphere around the instrument.

During the second project year the first two cameras were assembled. They were then tested at a RaDyO field experiment at Scripps Pier in January 2008. Following that, the profiling camera system was designed and built. All three cameras were then tested at a second RaDyO field experiment in Santa Barbara Channel in September, 2008.

A full field effort was completed in August-September, 2009, in the blue-water region south of Hawaii in the vicinity of 18° 00’N, 155° 30’W. Operations were carried out on the R/V Kilo Mauna (Lewis, Chief Scientist) where the surface reference and profiler was deployed, and the R/V FLIP where the independent RADCAM was deployed by the University of Miami team.

RESULTS

Hardware

Each of the cameras include a bandpass filter centered at 555 nm with a 20 nm bandwidth. The imaging chip is a very high dynamic range CMOS array. The scene dynamic range is 10^6 and the system dynamic range is nearly 10^{10}. The high scene dynamic range allows the sky and near surface radiance fields to be measured without needing to block the sun; the sun does not saturate the array or cause blooming. The field of view of each camera is 180 degrees. The resolution is 0.5 degrees on axis and drops to about 1 degree at large field angles. The frame rate is better than 7.5 fps, limited by the deck computer and software that records the video.

Three RadCam instruments are now in operation, as shown in Figure 1. All instruments contain the same high-dynamic range camera, but the reference camera is without a glass dome to reduce glare. It is designed to be mounted in a tripod or attached to a vertical pole. It transmits live video via a fiber optic cable. Like the other cameras it includes a tilt sensor and compass to orient the images to a fixed coordinate system. The second camera is designed to fit in a Bluefin AUV, but has also been mounted in its own cage and lowered from a winch. It logs all data internally but can be cabled with a low-speed Ethernet connection to provide a subsample of the video in near-real time over a virtual network connection.

The profiling system consists of both a downwelling and an upwelling camera, and ancillary sensors including a Falmouth Scientific CTD, multispectral radiance-irradiance head from Satlantic, and a Wetlabs transmissometer. It uses a fiber optic cable to transmit real-time video to the surface. It is designed to freefall through the water column. Tilts are generally less than 3 degrees and fall rates can be controlled from 0.3 to 1.0 m/s. We have also performed some fixed depth measurements with the profiler using a tethered float.

Initial Data

An example of the underwater light field from the Hawaii experiment is shown in Figure 2. The images are uncalibrated, but nicely show the Snell cone within the overall 180 degree field looking up.

Calibration

Calibration of the cameras consists of measuring the response function of the array to incident light and then calibrating the whole optical system to a known radiance. The response function is challenging due to both the high dynamic range and the high radiances involved. The response functions are highly nonlinear and vary from pixel to pixel, so every calibration data must be obtained for each pixel. Calibration data has been collected for all of the cameras and is being processed at this time.

Scattering in the optical system must also be characterized by measuring the point spread function (PSF). These exacting measurements were taken in the laboratory for a wide range of angles for each of the cameras. The entire image processing procedure will then be to apply calibration, deconvolve the images using the PSF, and finally correcting for tilt and heading changes.

a)  b)  c) 

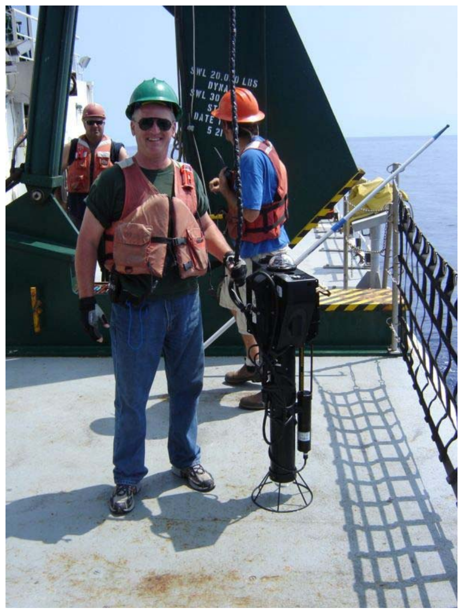
d) 

Figure 1:Photographs of three RadCam instruments are a) the in-air reference camera b) the logging camera mounted on a cage and being lowered into the water c) the logging camera mounted on an AUV (center of Bluefin) and d) the profiler camera system aft deck of the Kilo Moana prior to deployment.

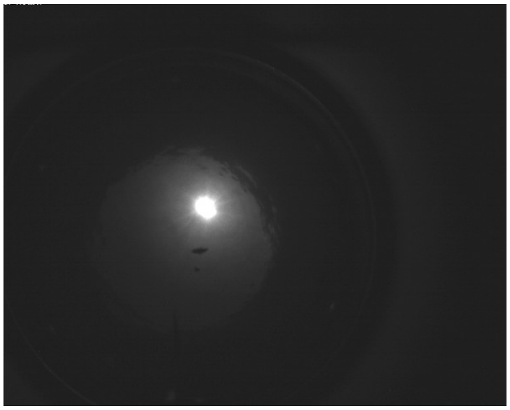
a)  b) 

Figure 2: Downwelling and upwelling radiance distribution. In panel a., the sun is clearly visible within the Snell cone (and with a fish present). The wave induced geometrical variability in the upwelling light field can be seen in the rays present in panel b.

For most of the cruise, sky radiance was collected at 30 s intervals throughout the day and will be available as both a qualitative and quantitative measure of the sky conditions during the cruise. This will be useful, as conditions tended to change rapidly (see Figure 3).

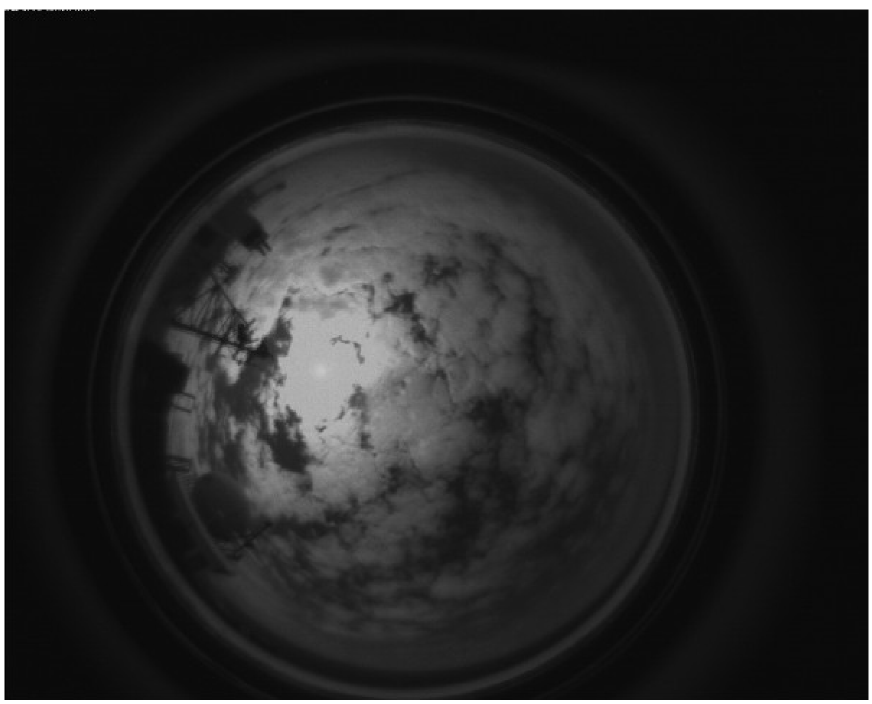


Figure 3: Downwelling sky radiance distribution during the Hawaii experiment. Note patchy cloud distribution and resulting complex radiance field.

Other results

Advances were made with respect to the application of precision radiometry in the upper ocean for derivation of satellite calibration and validation data sets (Voss et al., submitted), for the derivation of IOP's with a remarkable accuracy (Gordon et al. 2009), for elucidation of the influence of islands on upper ocean optics (Hasegawa et al. 2009) and for more general oceanographic applications (Schallenburg et al. 2008, Li et al. 2008, Lewis 2008, Moore et al. 2009).

IMPACT/APPLICATIONS

The camera may have applications for various sorts of surveillance. Radiometrically calibrated measurements of the in-air and in-water radiance distribution can be made. The derivation of optical properties from these measurements may have practical applications, as commonly made (but never tested or evaluated) assumptions can be directly assessed. It may be possible to derive all IOP measurements from the full radiance distribution and its vertical derivative. The shading effect of deployment platforms can be studied directly.

TRANSITIONS

A sky radiance distribution camera of the same design elaborated under this contract has been purchased by the Canadian forces (Defense Research Development Canada) for installation in aircraft.

RELATED PROJECTS

This project is embedded within the Radiance in a Dynamic Ocean (RaDyO) program, and hence is related to all projects contained therein. It is also related to the research programs of Dr. John Cullen, some of which are sponsored by ONR. Lewis has related projects funded through Dalhousie, and Lewis has related NASA-funded efforts through WetSat Inc.

PUBLICATIONS

Gordon, H.R., M.R. Lewis, S.D. McLean, M.S. Twardowski, S.A. Freeman, K.J. Voss and G.C. Boynton. 2009. Spectra of particulate backscattering in natural waters. *Optics Express* [refereed, in press].

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HONORS/AWARDS/PRIZES

Lewis, M.R.: Awarded Killam Professor of Oceanography, Dalhousie University, Killam Foundation.